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ANALYSIS OF TRAJECTORIES TO NEPTUNE USING GRAVITY ASSISTS

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At the present time the search for the knowledge of our Solar System continues effective. So, in July 1st, 2004, the international Cassini-Huygens Mission spacecraft entered into orbit around the planet Saturn and at the present time (January, 2005) it is sending data from the Huygens probe, which is studying Saturn's largest moon, Titan. NASA's Solar System Exploration theme listed a Neptune mission as one of its top priorities for the mid-term (2008-2013). The gravity assist is a proven technique in interplanetary exploration, as exemplified by the missions Voyager, Galileo, Cassini etc. Here a mission to Neptune for the mid-term (2008-2020) is proposed. Making the continuation of our previous work, the following schemes are analyzed: Earth–Jupiter–Neptune, Earth–Venus–Earth–Jupiter–Neptune, Earth–Venus–Earth–Jupiter–Saturn–Neptune. All the transfers are optimized in terms of the ΔV (characteristic velocity), in order to find a good compromise between the ΔV and time of flight to Neptune.

INTRODUCTION

The next step in the intensive exploration of the outer planets, following the Galileo and Cassini missions is a similar orbiter and atmospheric probe mission to Neptune. Neptune is scientifically a very interesting object because of its turbulent atmosphere and the presence of the large satellite Triton. Triton is particularly interesting because of its size, retrograde orbit, and the insight into Solar System cosmogony to be gained through its comparative relationship with Pluto and Charon.

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Several authors[1] proposed missions to the Neptune system, comprised of an orbiter and a Neptune atmospheric multi-probe. In the decade of the 60's, some works[2] planed a mission to the exterior Solar System using the concepts of gravity assist maneuvers with Jupiter, Saturn, Uranus. This type of trajectories was used for the Voyager 2. Some works[3] analysed the trajectory of the Voyager 2 and the gravity assisted maneuver with Jupiter, Saturn, Uranus and Neptune. However, the possibility of multiple gravity maneuver (Earth and Venus) for a trip to Neptune is also possible[4]. Moreover, exist several proposed trips for the outer solar system[5] (Uranus, Neptune, Pluto).

There are other works utilizing propulsive maneuvers, to avoid the disadvantage of the planetary configuration necessary for the gravity assists maneuver. Some studies[6] considered the exploration of Neptune with aerocapture maneuver, and combination with radioisotope power source and solar electric propulsion. Other projects considered the use of solar electric energy, Earth gravity assists and aerocapture maneuver to achieve Neptune and Triton[7] (Neptune and Triton explorer "NExTEP"). There is also improvements to the use of solar and radioisotope electric propulsion system for a trip to Neptune utilizing combinations with the chemical system[8]. Other works[9-10] studied the combination of propulsive and gravity assist maneuvers for this trip.

We are interested in the gravity-assisted maneuvers without the use of propulsive maneuvers. The lack of power resources is compensated with several gravity-assisted maneuvers. They demand a long time, which is necessary for phasing the spacecraft trajectory and the flyby planets. For interplanetary flight trajectories it is admissible to approximate the legs of the flight before and after the gravitational maneuver by arcs of conic sections. These arcs are unambiguously determined by the launch instant, the instant of flyby near the intermediate planet, and the instant of the spacecraft arrival to the destine planet.

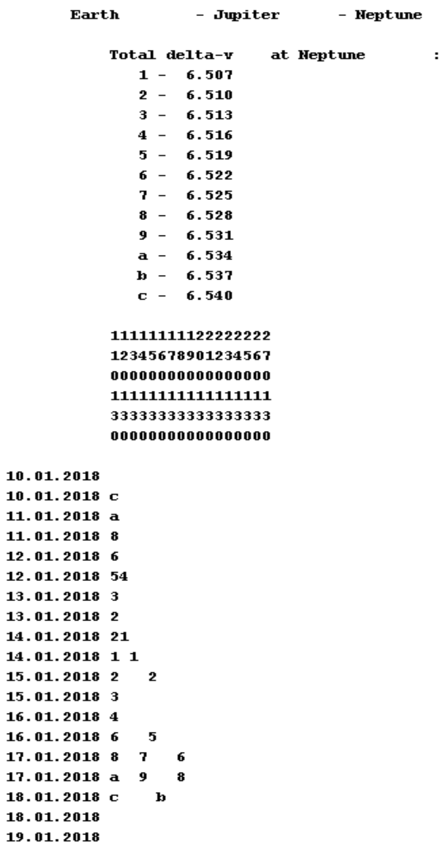
ANALYSIS OF TRAJECTORIES TO NEPTUNE

Our previous work[11] show that the best scheme with and without braking are represented by the Earth-Jupiter-Neptune (EJN), Earth-Venus-Earth-Jupiter-Neptune (EVEJN) and Earth-Venus-Earth-Jupiter-Saturn-Neptune (EVEJSN) transfers. In this work our goal is to study in more detail the mentioned schemes.

Pork-chop and Variation of Pericenter Height.

The pork-chop shows the optimized total ΔV for a trip to Neptune, considering the EJN and EVEJN schemes and excluding the costs of breaking near Neptune as a function of the dates of launch and arrival. The numbers 1 to 9, and the letters a, b, c, represent the diverse values of the total ΔV. Figure 1 show the window of interest for the EJN scheme, considering a time of flight of 12 years, between 10/01/2018 and 19/01/2018, in which interval we find that the total ΔV are between 6.507 km/s and

6.540 km/s. However we observe in Figure 1 the repetition of the dates. We choose a step of 12 hours with respect to the Earth. The spacecraft flyby Jupiter with a height of 424.5x10^3 km. Figure 2 shows similar characteristics to Figure 1 for the EVEJN scheme, however as the time of flight is 18 years, the flyby Jupiter height is 1399.6x10^3 km. Figure 3 shows the planetary configuration for the Earth-Jupiter-Neptune scheme for a time of flight of 12 years, the Earth-Venus-Earth-Jupiter-Neptune scheme for a time of flight of 18 years and the Earth-Venus-Earth-Jupiter-Saturn-Neptune scheme for a time of flight of 12 years. All the bodies are in the plane of the ecliptic. All our schemes of transfers are positive, however some work studied several retrograde trajectories, but the transfer time is too long. In this analysis[5] it was shown several trajectories to Pluto, through Jupiter-Uranus-Neptune, finding retrograde trajectories for launches after 1996, which extend up to 2005. From the point of view of the energy provided by the planets, we have that the main contributions comes from of Jupiter, Saturn, Venus and Earth. Considering this fact and also that our better trajectories (EJN, EVEJN, EVEJSN) consider flyby in Jupiter, we will make an analysis of the variations in the pericenter height near Jupiter and its consequences in the fuel consumption. Figure 4 shows the behavior of the total ΔV as a function of the pericenter height. For the analysis of the EJN scheme, we consider the transfer time fixed and from a certain value of the pericenter height, we analyzed the behavior of the optimal total ΔV with the variation of pericenter height.



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       Earth        - Jupiter       - Neptune

           Total delta-v    at Neptune         :
              1 -  6.507
              2 -  6.510
              3 -  6.513
              4 -  6.516
              5 -  6.519
              6 -  6.522
              7 -  6.525
              8 -  6.528
              9 -  6.531
              a -  6.534
              b -  6.537
              c -  6.540

           11111111122222222
           12345678901234567
           00000000000000000
           11111111111111111
           33333333333333333
           00000000000000000

10.01.2018
10.01.2018 c
11.01.2018 a
11.01.2018 8
12.01.2018 6
12.01.2018 54
13.01.2018 3
13.01.2018 2
14.01.2018 21
14.01.2018 1 1
15.01.2018 2   2
15.01.2018 3
16.01.2018 4
16.01.2018 6   5
17.01.2018 8  7   6
17.01.2018 a  9   8
18.01.2018 c    b
18.01.2018
19.01.2018
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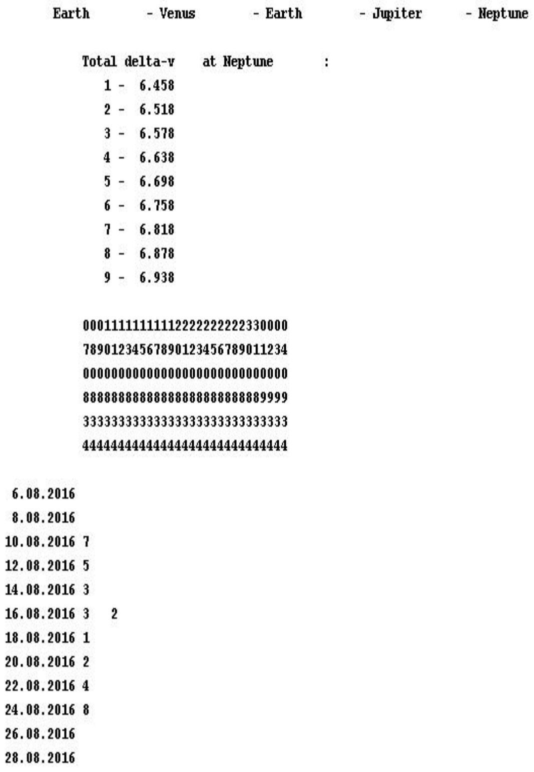
Figure 1 Pork-chop for the Earth-Jupiter-Neptune scheme.



```
       Earth         - Venus         - Earth         - Jupiter        - Neptune

            Total delta-v     at Neptune       :
               1 -  6.458
               2 -  6.518
               3 -  6.578
               4 -  6.638
               5 -  6.698
               6 -  6.758
               7 -  6.818
               8 -  6.878
               9 -  6.938

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  6.08.2016
  8.08.2016
 10.08.2016 7
 12.08.2016 5
 14.08.2016 3
 16.08.2016 3   2
 18.08.2016 1
 20.08.2016 2
 22.08.2016 4
 24.08.2016 8
 26.08.2016
 28.08.2016
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Figure 2 Pork-chop for the Earth-Venus-Earth-Jupiter-Neptune scheme.

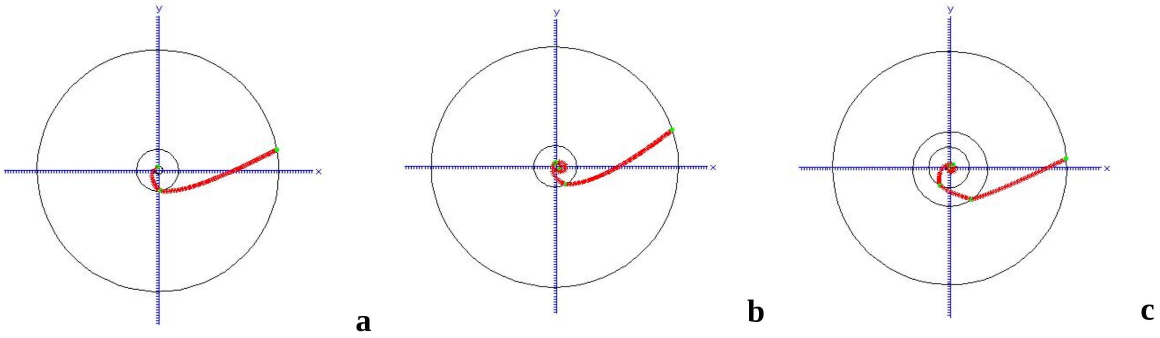

Figure 3 Planetary configuration and transfer trajectory: (a) Earth-Jupiter-Neptune scheme for 2018, (b) Earth-Venus-Earth-Jupiter-Neptune scheme for 2016, (c) Earth-Venus-Earth-Jupiter-Saturn-Neptune scheme for 2015.

For the transfer time of 12 years, the pericenter height in Jupiter is 420x10^3 km. In the several simulations we can see that, when vary the pericenter height of flyby in Jupiter (that is the only case in consideration) the optimal value has several changes. Thus, with a time of flight of 12 years and a height of 600x10^3 km the optimal value for the total ΔV is 7.891 km/s. This is approximately an addition of 20% with respect to its optimal initial value. For a time of flight of 14 years the height vary between 670x10^3 km and 900x10^3 km for the simulations considered. The optimal value is 6.412 km/s. However, the maximum value considered in the present simulation suffers an addition of 11% with respect to the initial value. The same Figure 4a shows that, when the time of flight is 18 years, the optimal value is 6.355 km/s showing pericenter height variations of 1040x10^3 km and 1300x10^3 km. The optimal value is 6.355 km/s, suffering an addition of 13%.

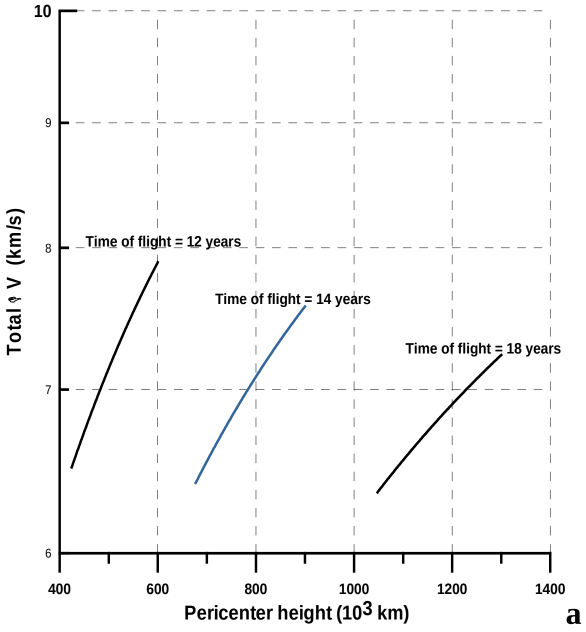

Figure 4 Total ΔV vs. pericenter height for the EJN scheme.

In a general way, as we vary the pericenter height of flyby at Jupiter, we see that the total ΔV suffer additions from the optimal value. This same fact happens for the others schemes.

Low Earth Orbit (LEO) and Geostationary Orbit (GTO) Transfer

Figure 5 shows the best schemes with and without braking. The analysis has the objective of studying the behavior of the launch ΔV for each one of the schemes. The differences for the schemes considered are minimum, however the EVEJN and EVEJSN schemes suffer smaller additions, which means that, to reach the desired configuration it is necessary to increase the launch velocity. The EVEJSN scheme presents the lowest values for the launch ΔV, and it has the optimal value when compared with the other schemes. In all the simulations the time of flight were considered between 12 and 18 years. The EVEJN scheme shows intermediate values for the launch ΔV. The EJN scheme has a small reduction in the launch ΔV for a fixed time of flight, but compared with the other schemes it has advantages from the point of view of the launch ΔV. Considering the schemes with breaking, Figure 6 shows the behavior of the characteristic energy and of the optimal total ΔV for the several dates of launch.

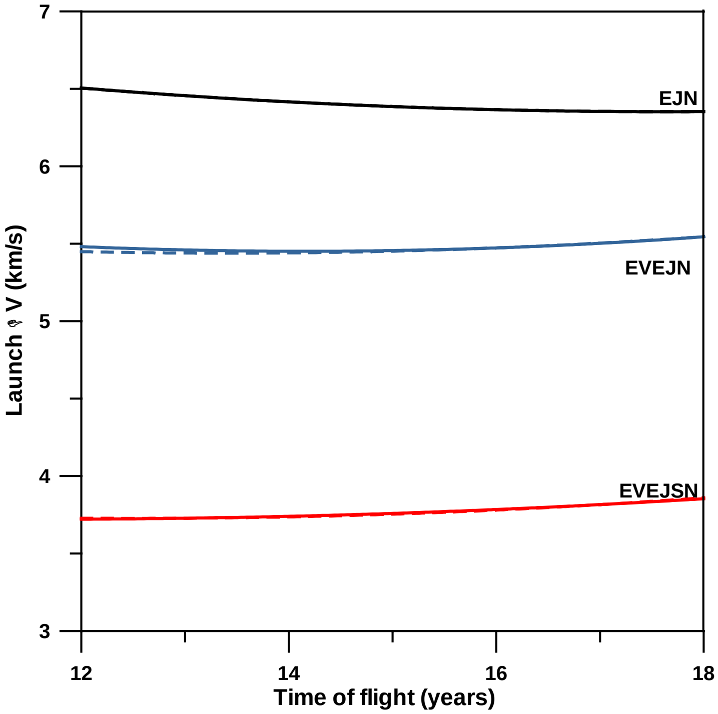

Figure 5 Launch ΔV for several schemes (full lines without braked final and the dashed lines with braked final).

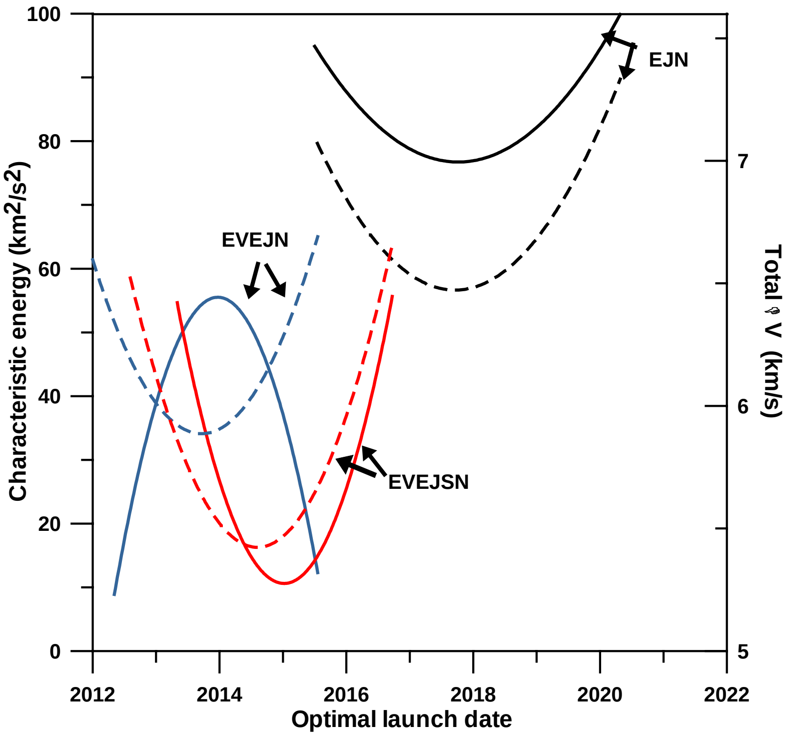

Figure 6 Characteristic energy vs. optimal launch date for trajectories with breaking (full lines characteristic energy and the dashed lines total ΔV).

Let us remember that the characteristic energy is the energy necessary for departure from the planet's sphere of influence, in the present case the energy to escape from the sphere of influence of the Earth. The values of the optimal total ΔV were analyzed previously[11], however, here, the research is performed only for the best schemes (EJN, EVEJN, and EVEJSN) considering braking. The full and dashed lines represent the characteristic energy and the optimal total ΔV. The EJN scheme shows the largest values of the characteristic energy and the optimal total ΔV when compared with other schemes. The curves that represent the characteristic energy and the optimal total ΔV have a similar behavior, which means that, for the optimal date we have the minimum values for the optimal total ΔV and for the characteristic energy. The EVEJN scheme has a anti-symmetrical behavior (mirror type) in relation to the characteristic energy and the optimal total ΔV. In this case, a high characteristic energy is necessary to optimize the total ΔV as a function of the date of the launch. From the maneuvers with Venus, Earth, Jupiter and Saturn contributions to the energy required to reach Neptune, the one that has minimum characteristic values for the energy is given by the EVEJSN scheme. This scheme has low values for the characteristic energy. All the previous simulations had been made considering the launch from LEO orbit, however, to follow our objective, that is to analyze the advantages or disadvantage, we used a GTO orbit, because it is the case of the launch vehicles Titan IV, that was used for the launching of the Cassini.

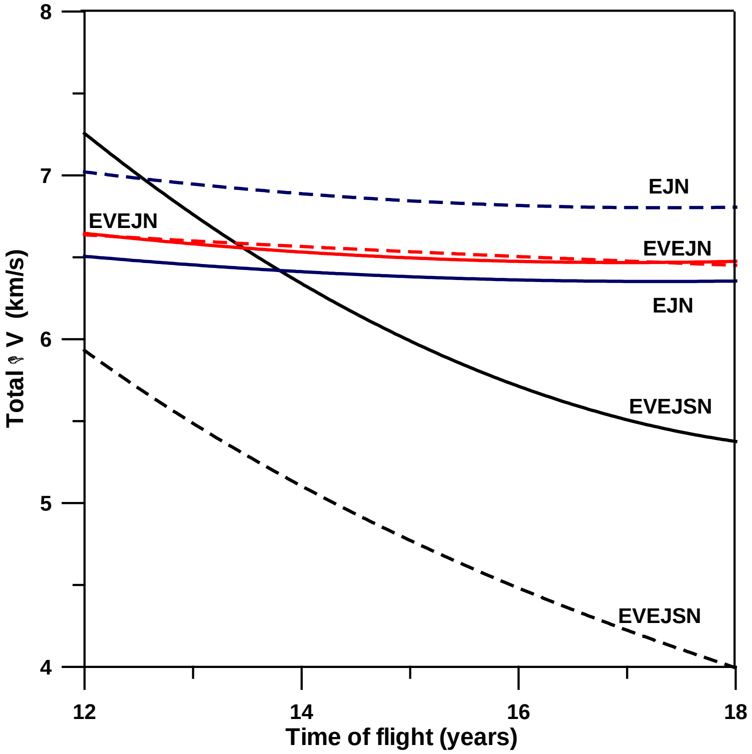

Figure 7 Total ΔV without breaking. The full and the dashed lines show the launch from LEO and GTO

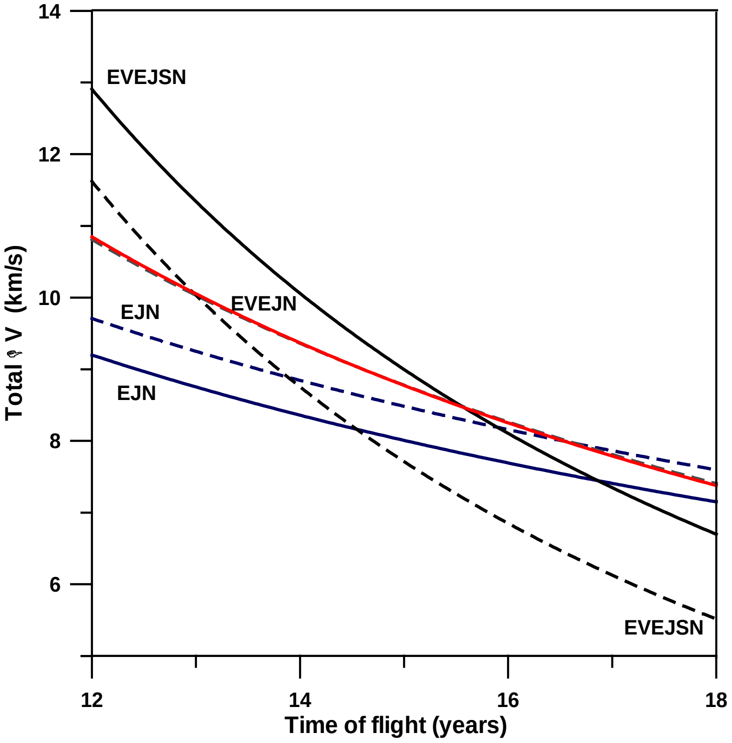

Figure 8 Total ΔV with breaking. The full and dashed lines show the launch from LEO and GTO.

The GTO is an intermediate orbit between the LEO and the geostationary orbits (GSO). In this case the ellipse has a perigee in an LEO orbit and its apogee in a GSO orbit. Figure 7 shows the optimal total ΔV for several times of flight. The full lines had been presented previously when we analyzed the optimal ΔV for several schemes. However, the use of an orbit of transference GTO (dashed lines) brings certain advantages or disadvantages depending on the scheme. The EVEJSN schemes without breaking considering a GTO transfer is better than the others schemes. For a time of flight of 12 years the total ΔV is 5.894 km/s (GTO). When considering the case of launching from LEO orbit, this option presents an optimal total ΔV larger than the other schemes. For times of flight near 17 years (GTO), the optimal total ΔV is 4.216 km/s. The EJN scheme, that presented the best values for the optimal total ΔV for times of flight near 14 years for a LEO orbit, in the case of a GTO orbit shows an addition in the total ΔV. We consider, in a first approach, that for the configuration of the mentioned planets (Earth-Jupiter-Neptune), this type of transference (GTO) does not contribute too much to reduce the total ΔV. Due to the configuration presented for the year 2018, it is necessary to increase the launch ΔV to be able to reach Jupiter. This fact makes the total ΔV to have an addition for this scheme.

Table 1
V_∞ for EVEJN scheme

Time of flight (years)	Launch height ($X10^3$km)	Date of launch	Neptune V_∞ (km/s)	Earth V_∞ (km/s)
12	35.79	26/08/2016	14.569	7.160
12	0.2	24/08/2016	14.651	7.401
15	35.79	18/08/2016	9.980	7.572
15	0.2	18/08/2016	9.980	7.632
16	35.79	22/08/2016	8.920	7.121
16	0.2	20/08/2016	8.925	7.386

The energy necessary to escape from the sphere of influence of the Earth does not make greater changes, when considering several orbits of launch (LEO and GTO). Also, the pericenter height near Jupiter does not suffer greater changes for the LEO and GTO orbits. The EVEJN scheme has small modifications when considering several types of launching orbits. According to Figure 7, there are regions where the LEO scheme is of lower consumption than the GTO orbit and, with others, occurs the opposite. The changes in the excess velocity are shown in Table 1.

The variations in the pericenter height near Venus, Earth and Jupiter are small. Figure 8 shows the case where the braking near Neptune is included. The dashed lines represent several schemes considering the braking and the fact that the launch orbits are GTO. The EVEJSN scheme is optimal for a time of flight of 17 years for the case of a

LEO orbit. To consider the case of the GTO orbit, there is a displacement, being optimal for times of flight near 15 years. The several values of the optimal total ΔV are shown in Table 2. The EJN scheme that considers a LEO orbit show values smaller than the other schemes, considering times of flight of 15 years (Figure 8). However, considering GTO orbit, the EJN scheme continues being optimal until a time of flight of 14 years. The EVEJN scheme has a small improvement when considering a GTO orbit. However, the interval is short for, which the fuel consumption is smaller than the EVEJSN scheme. The use of one or another scheme considering its advantages or disadvantages, is a function of the objectives of the mission.

Table 2 Total and launch ΔV for EVEJSN scheme with breaking

Time of flight (years)	Launch height ($X10^3$km)	Date of launch	Launch ΔV (km/s)	Total ΔV (km/s)
12	35.79	12/06/2015	2.434	11.616
12	0.2	11/06/2015	3.728	12.906
13	35.79	10/06/2015	2.420	10.037
13	0.2	11/06/2015	3.728	11.341
17	35.79	07/06/2015	2.562	6.126
17	0.2	05/06/2015	3.816	7.347

The LEO and GTO orbits do not change the pericenter height of flyby in Venus, Earth, Jupiter, Saturn. Figures 9 and 10 show the values of the optimal launch ΔV for the several schemes considering launch from LEO and GTO. Considering the transfer with and without braking, we find that do not exist differences between both figures. However, the EVEJSN scheme shows minimum values. Thus, for a time of flight of 12 years, the launch ΔV from LEO orbit is 3.722 km/s and the launch ΔV for GTO orbit is 2.404 km/s. When considering times of flight larger, the curve suffers small additions, thus, for a time of flight of 17 years the LEO orbit has a launch ΔV of 3.816 km/s and the GTO orbit has a launch ΔV of 2.562 km/s. Remember that this option, when considering the braking, is better than the other schemes for times larger than 17 years from LEO orbits and 14 years from GTO orbits. Moreover, there is an improvement in the values of the launch ΔV for the EVEJN scheme. Previously, we study the advantages and disadvantages of this scheme from the point of view of the total ΔV. Figure 11 shows the braking ΔV as a function of the time of flight for several schemes. The fact of considering LEO or GTO orbits does not modify the fuel consumption necessary to break the spacecraft near Neptune. However, the EJN scheme presents smaller ΔV for braking, when compared with the EVEJN and EVEJSN schemes.

Table 3 shows that, for a time of flight of 12 years the ΔV for braking is 2.791 km/s. Moreover, as we have seen in Figure 8, this scheme is better that the others for a time of flight near 15 years (LEO) and for a time of flight near 14 years (GTO). The ΔV braking suffers a reduction of 35,43% (for 14 years) when compared in a time of flight of 12 years. From the point of view of the optimal total ΔV and of the braking ΔV, the Jupiter gravity assist is optimal when considering times of flight near 15 years. For a time of flight of 18 years, there is a reduction of 53.33% when compared to the value for a transfer of 14 years. But, as we have analyzed for times of flight between the 15 and 17 years, the EVEJSN scheme is better with a GTO orbit. However, it the case of LEO orbit, this continues being optimal with low fuel consumption low.

Table 3 Braking ΔV for EJN scheme

Time of flight (years)	Launch height (X10^{3}km)	Date of launch	Braking ΔV (km/s)	Total ΔV (km/s)
12	35.79	14/01/2018	2.791	9.814
12	0.2	14/01/2018	2.791	9.298
14	35.79	14/01/2018	1.802	8.691
14	0.2	14/01/2018	1.802	8.215
18	35.79	14/01/2018	0.841	7.647
18	0.2	14/01/2018	0.841	7.196

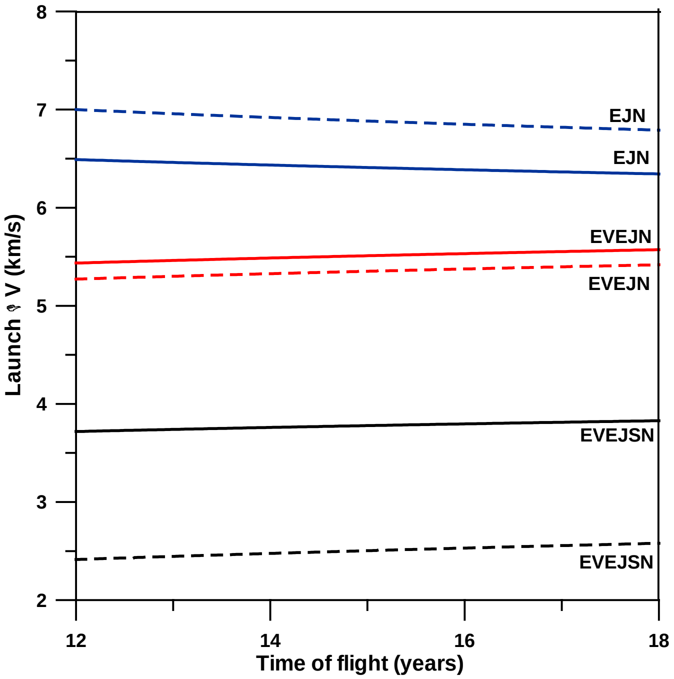

Figure 9 Launch ΔV for schemes without breaking. The full and dashed lines show the LEO and GTO transfer.

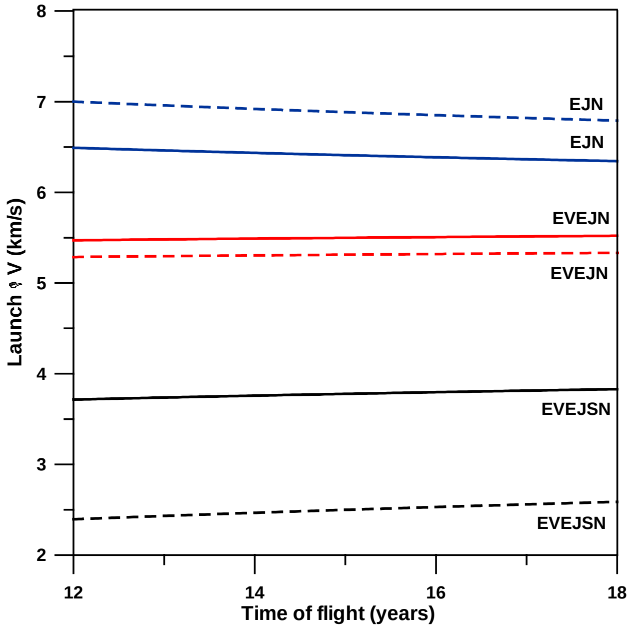

Figure 10 Launch ΔV for schemes with breaking. The full and dashed lines show the LEO and GTO transfer.

Figure 10 shows the EVEJSN scheme considering a GTO orbit. It has fuel consumptions smaller than the others schemes. However, Figure 11 shows that the braking ΔV is raised for this scheme. Thus, for example, for a time of flight of 12 years, the braking ΔV is 5.702 km/s. This represents 51% more fuel consumption than the EJN scheme for the same time of flight. Considering the compromise between the fuel consumption and time of flight, we see that the EJN scheme shows the best values for the braking ΔV, being its disadvantage that the fuel consumption is high in the launch ΔV. The total ΔV is optimal until a certain interval of time, however its characteristic energy is high (Figure 6).

The contribution of the LEO and GTO orbits to the optimal ΔV, considering the braking as a function of optimal dates is shown in Figure 12. The EVEJSN scheme for GTO orbit has great improvements when compared to the EVEJSN scheme for LEO orbit. The value is near 4.4 km/s, suffering a fast displacement for the optimal date with respect to the optimal date for a launch from LEO orbit. The EVEJN scheme launched from a GTO orbit also has improvements when compared to the launch from LEO orbit. An interesting point, depending on the objectives of the mission, is the fact that the fuel consumptions for EVEJSN scheme launches from LEO orbit and the EVEJN scheme to launch from GTO orbit are the same. Moreover, the optimal dates to reach the mission successfully are close to each other. The behavior of EJN scheme is similar to the case analyzed for optimal total ΔV with breaking for several types of launching orbits, or either the fact to consider an orbit of launching to GTO does not bring advantages for this scheme.

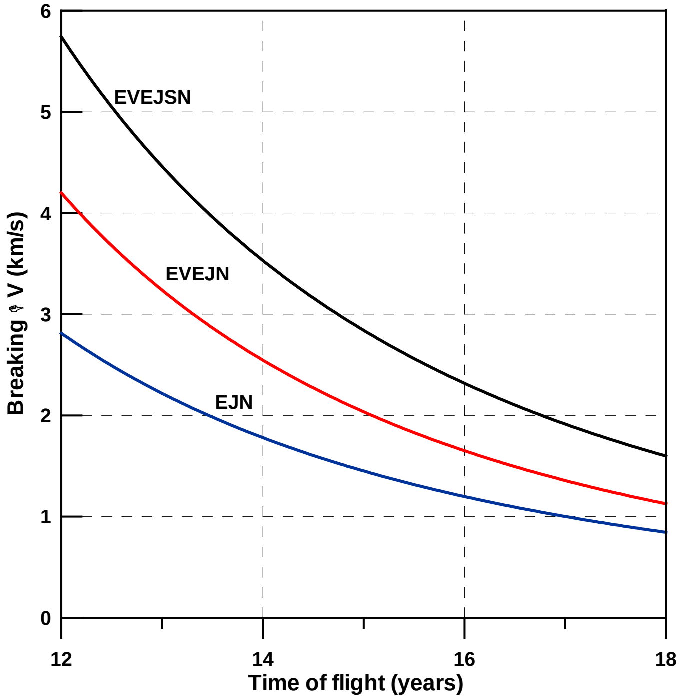

Figure 11 Breaking ΔV for several transfer schemes.

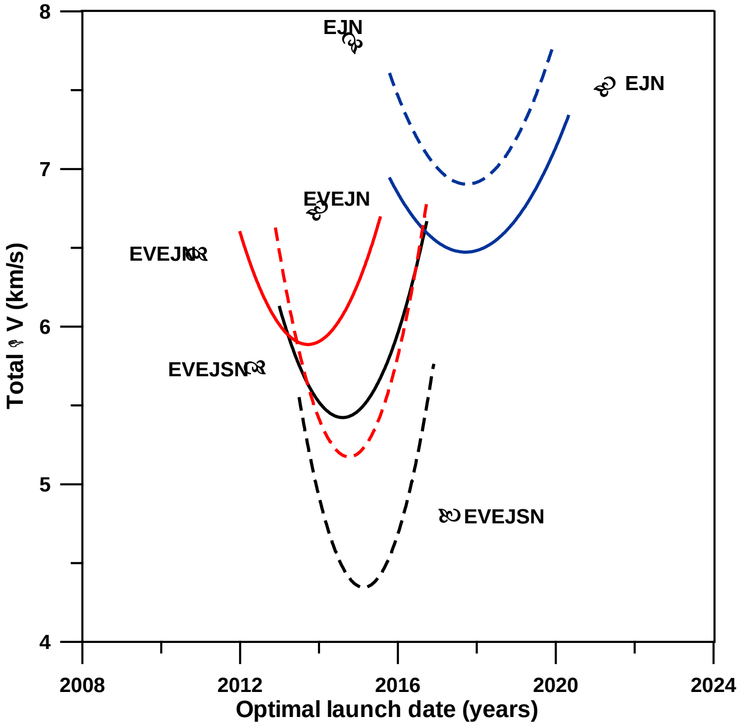

Figure 12 Optimal launch. The full and dashed lines show the LEO and GTO transfer

CONCLUSIONS

In this paper, the minimum total ΔV is obtained as a function of the launch date and flight duration. This parameter determines the fuel consumption to launch from LEO, GTO and breaking the spacecraft near Neptune. Moreover, we analyse the effect of the variation in the pericenter height near Jupiter and its effect in the fuel consumption. The several orbits of launching (LEO and GTO) have advantages or disadvantages for each one of the schemes of transfer considering the effect with and without brake. All our schemes of transfers are positive, however some other work[5] studied several retrograde trajectories for which the transfer time is too long. This analysis showed several trajectories for Pluto, through Jupiter-Uranus-Neptune, finding retrograde trajectories for launchings after 1996, which extend up to 2005. In this paper we have considered the Venus, Earth, Jupiter gravity assists showing its advantages on the configuration of the planets in specific dates. Thus a Jupiter flyby offers the most gain of the impulsive trajectory alternatives. Such a transfer is available for Earth departures in 2005, 2006, and 2007 and, after that, only about 2017[12]. However, Venus is available and offers good results for launching from Earth in mid-term 2012-2016. All the previous schemes allow a close approach to Neptune and, depending on the objectives of the mission, we can make a flyby or remain in orbit around of some of moons of the planet.

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